Exoplanet Exploration Program Update

Dr. Gary H. Blackwood, Program Manager

NASA Exoplanet Exploration Program

Jet Propulsion Laboratory

California Institute of Technology

June 06, 2017

230th Meeting of the American Astronomical Society

Austin, Texas

Artist concept of Kepler-16b
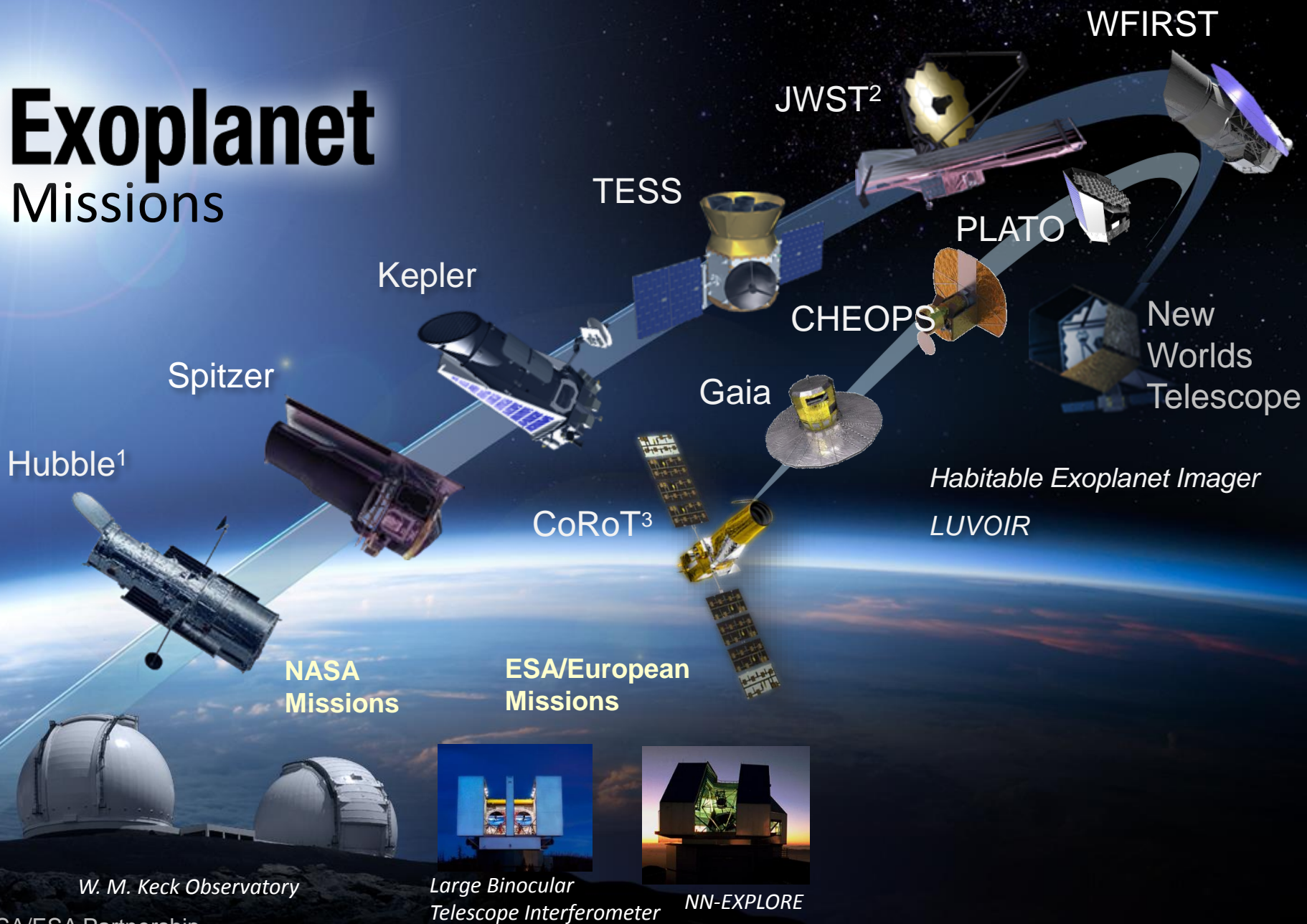Credit: NASA/JPL-Caltech/T. Pyle

Exoplanet
Missions

WFIRST

JWST[2]

TESS

PLATO

Kepler

CHEOPS

New
Worlds
Telescope

Spitzer

Gaia

Hubble[1]

Habitable Exoplanet Imager

CoRoT[3]

LUVOIR

**NASA
Missions**

**ESA/European
Missions**

W. M. Keck Observatory

*Large Binocular
Telescope Interferometer*

NN-EXPLORE

[1] NASA/ESA Partnership
[2] NASA/ESA/CSA Partnership
[3] CNES/ESA

Ground Telescopes with NASA participation

2

NASA Exoplanet Exploration Program

Space Missions and Mission Studies

Kepler, K2

WFIRST

Decadal Studies

Starshade

Coronagraph

Public Communications

EYES ON EXOPLANETS
explore a visual database of new worlds

Supporting Research & Technology

Key Sustaining Research

Large Binocular Telescope Interferometer

Keck Single Aperture Imaging and RV

Technology Development

Coronagraph Masks

High-Contrast Imaging

Deployable Starshades

NASA Exoplanet Science Institute

Explore New Worlds
NASA's Exoplanet Exploration Program

Archives, Tools, Sagan Fellowships, Professional Engagement

https://exoplanets.nasa.gov

ExEP is a Program Office within the NASA Astrophysics Division

Astrophysics Division, NASA Science Mission Directorate

Resource Management
Omana Cawthon+
Clemencia Gallegos-Kelly+

Director
Paul Hertz
Deputy Director
Andrea Razzaghi

Lead Secretary: Kelly Johnson
Secretary: Kyle Nero
Program Support Specialist: Jackie Mackall

Cross Cutting
Technology Lead: Billy Lightsey*
Education POC: Hashima Hasan (Lead Comm Team)
Public Affairs Lead: Kartik Sheth
Information Manager: Lisa Wainio*
Strategic Planning: Rita Sambruna

Astrophysics Research
Program Manager: Dan Evans
Program Support: Ingrid Farrell*
Astrophysics Data Analysis: Doug Hudgins
Astrophysics Theory:Keith MacGregor*
Exoplanet Research: Martin Still*
APRA lead:Michael Garcia*
Cosmic Ray, Fund Physics: Thomas Hams*, Vernon Jones,
Keith MacGregor*, Rita Sambruna
Gamma Ray/X-ray: Dan Evans, Michael Garcia*, Stefan
Immler*, Rita Sambruna,Wilt Sanders
Optical/Ultraviolet: Michael Garcia*, Hashima Hasan,
Mario Perez*, Martin Still*
IR/Submillimeter/Radio: Dominic Benford*, Doug Hudgins,
Kartik Sheth, Eric Tollestrup*
Lab Astro: Doug Hudgins
Theory & Comp Astro Net:Keith MacGregor*
Roman Tech Fellows: Billy Lightsey*
Data Archives: Hashima Hasan
Astrophys Sounding Rockets: Wilt Sanders
Balloons Program: Vernon Jones(PS), Mark Sistilli (PE)

Programs / Missions & Projects

	Program Scientist	Program Executive
Exoplanet Exploration (EXEP)		
Program	**Doug Hudgins**	**John Gagosian**
Keck	Hashima Hasan	Mario Perez*
Kepler/K2	Mario Perez*	Jeff Hayes
LBTI	Doug Hudgins	Mario Perez*
NN-EXPLORE	Doug Hudgins	Mario Perez*
WFIRST	Dominic Benford*	John Gagosian
Cosmic Origins (COR)		
Program	**Mario Perez***	**Shahid Habib**
Herschel	Dominic Benford*	Jeff Hayes
Hubble	Michael Garcia*	Jeff Hayes
SOFIA	Hashima Hasan	Shahid Habib
Spitzer	Kartik Sheth*	Jeff Hayes
Webb^	Hashima Hasan	Ray Taylor^
Physics of the Cosmos (PCOS)		
Program	**Rita Sambruna**	**Shahid Habib**
Athena	Michael Garcia*	Jeanne Davis
Chandra	Stefan Immler*	Jeff Hayes
Euclid	Eric Tollestrup*	Shahid Habib
Fermi	Stefan Immler*	Jeff Hayes
Planck	Rita Sambruna	Jeff Hayes
ST-7/LPF	Rita Sambruna	Shahid Habib
XMM-Newton	Stefan Immler*	Jeff Hayes
Astrophysics Explorers (APEX)		
Program	**Wilt Sanders**	**Jeanne Davis**
GUSTO	Thomas Hams*	TBD
IXPE	Eric Tollestrup*	Mark Sistilli
NICER	Rita Sambruna	Jeanne Davis
NuSTAR	Lou Kaluzienski	Jeff Hayes
Swift	Martin Still*	Jeff Hayes
TESS	Martin Still*	Mark Sistilli
XARM	Dan Evans	Jeanne Davis

+ Member of the Resources Management Division
* Detailee, IPA, or contractor
^ Webb is part of the JWST Program Office.

April 04, 2017

Exoplanet Exploration Program
Astrophysics Division, Science Mission Directorate

**Program Office
(JPL)**

PM- Dr. G. Blackwood
DPM- K. Short
Chief Scientist – Dr. K. Stapelfeldt
Chief Technologist – Dr. N. Siegler

Program Analysis Group
(ExoPAG)
Dr. A. Boss, EC chair

Technical Analysis Committee
(ExoTAC)
Dr. A. Boss, chair

Program Science Office

PCS- Dr. K. Stapelfeldt
DPCS- Dr. E. Mamajek

Program Engineering Office

Chief Engineer
K. Warfield

**Program Business Admin
Office**

Mgr- R. Lemus

Kepler Mission Management
Manager – K. Short (acting)

Business Operations

Resources – B. Nomoto
Schedule – G. Luzwick

WFIRST Mission Management
Manager – A. Comberiate
Business Mgr. – S Keasler

**Program
Communications
(JPL)**

Mgr – A. Biferno

**Kepler Project
(ARC)**

PM – C. Sobeck
PS – Dr. N. Batalha
PS (K2) – Dr. J. Dotson

**Program Technology
(JPL)**

Mgr– Dr. N. Siegler
Deputy – Dr. Brendan Crill

LBTI Project

PM – Dr. P. Willems, JPL
PI – Dr. P. Hinz, UA
PS – Dr. C. Gelino, Caltech

**WFIRST Project
(GSFC)**

PM – K. Grady
DPM – C. Peddie
PS – Dr. J. Kruk

**Universe of Learning
(JPL)**

Mgr – A. Biferno Co-I

**Starshade Technology
Project
(JPL)**

PM – Dr. J. Ziemer

NN-EXPLORE Project

PM – Dr. J. Callas, AD, JPL
PI - Dr. S. Mahadevan, PSU
PS – Dr. R. Capps, JPL

NExScI (Caltech)

Ex Dir– Dr. C. Beichman
DD – Dr. D. Gelino
Chief Scientist – Dr. D. Ciardi
Mgr – Dr. R. Akeson (acting)

**Coronagraph Instrument
(JPL)**

PM – Dr. M. Frerking
DPM – Dr. F. Zhao
PS – Dr. J. Rhodes
DPS - Dr. L. Moustakas

Astrophysics Division: Driving Documents

Results of NWNH:

- WFIRST is top large-scale recommended activity

- NWNH technology program is top medium-scale recommended activity
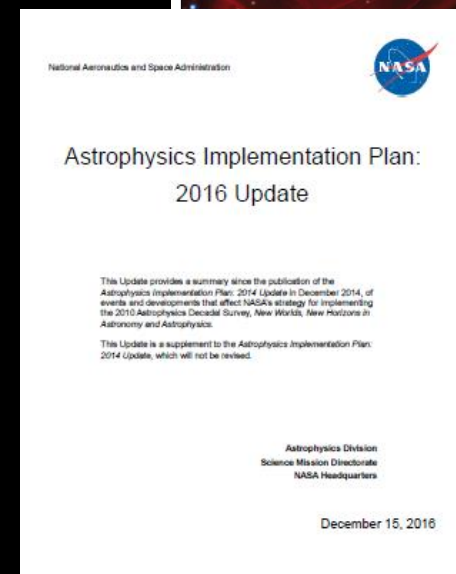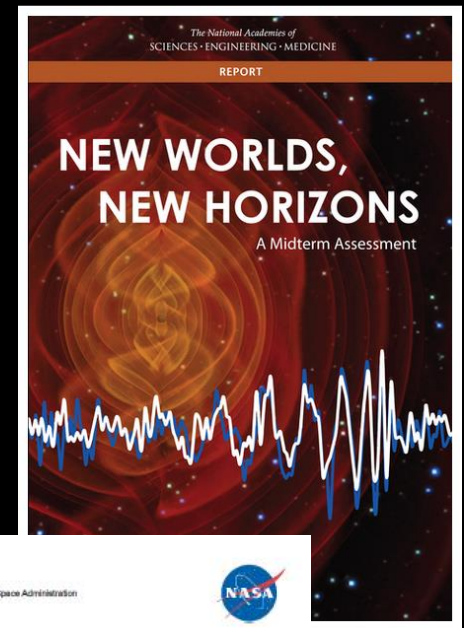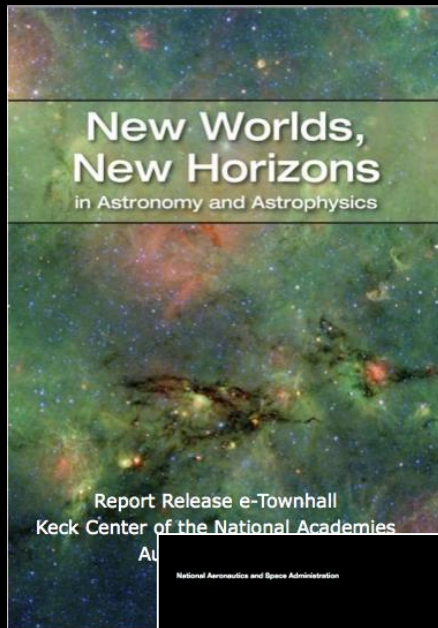
http://science.nasa.gov/astrophysics/documents

NASA Exoplanet Exploration Program

Astrophysics Division, NASA Science Mission Directorate

NASA's search for habitable planets and life beyond our solar system

Program purpose described in
2014 NASA Science Plan

1. Discover planets around other stars
2. Characterize their properties
3. Identify candidates that could harbor life

ExEP serves the science community and NASA by implementing NASA's space science vision for exoplanets

https://exoplanets.nasa.gov

Exoplanet Exploration Program

Serving the exoplanet science community by implementing NASA's space science vision for exoplanets

	Today	Enabled Science	Future	Enabled Science
Discover				
Characterize				
Identify Worlds that Could Harbor Life				
Community Support				

Show Me the Planets!

You Had Me at Habitable

Show Me the Planets!
Enabling Science Today

	Today	Enabled Science
Discover	• Kepler	• Occurrence rates for science and design of future missions
	• K2	• Discoveries via photometry and microlensing, potential JWST Targets
Characterize	• NASA Keck time	• SMD Science, Exoplanet follow up and precursor science
	• NNEXPLORE GO, including NESSI	• Exoplanet Science
	• NASA Exoplanet Archive	• Orbit prediction and observability for space missions for all exoplanets and user targets. • Table of transmission spectroscopy data including from HST and Spitzer.

Kepler Close-Out

Delivering Kepler's Legacy

- Kepler closeout and final data processing continues steadily within overall schedule margin

- SOC 9.3 Final Occurrence Rate Products planned for June 2017

KEPLER&K2
2017 SciConIV

JUNE 19-23 2017

NASA Ames Research Center
Moffett Field, CA

Credit: NASA/ARC
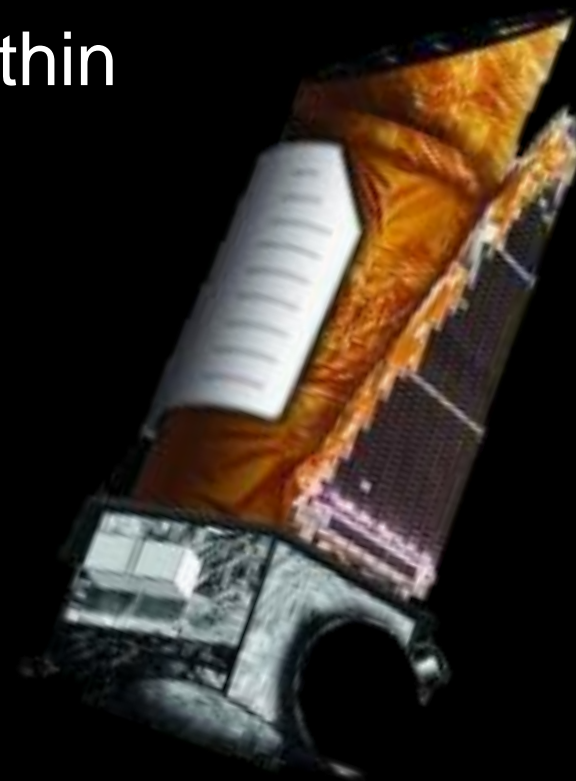
Kepler K2

Extending the Power of Kepler to the Ecliptic
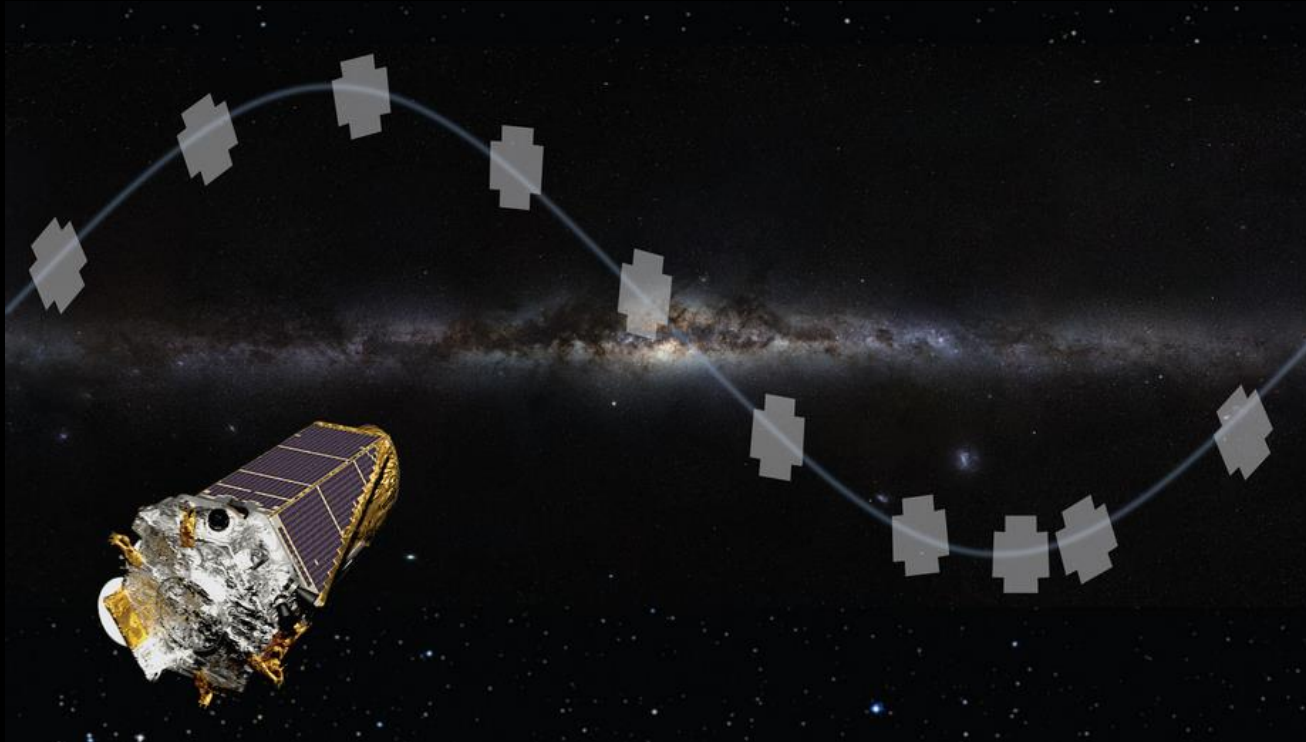
Upcoming

- Changed the position of the field for Campaign 16 – Kepler will observe in the forward-facing direction; emphasis on supernova science
- Release of Microlensing results from Campaign 9

https://exoplanets.nasa.gov/k2

"Mamajek's Law"
Exoplanet Discovery Doubling Time
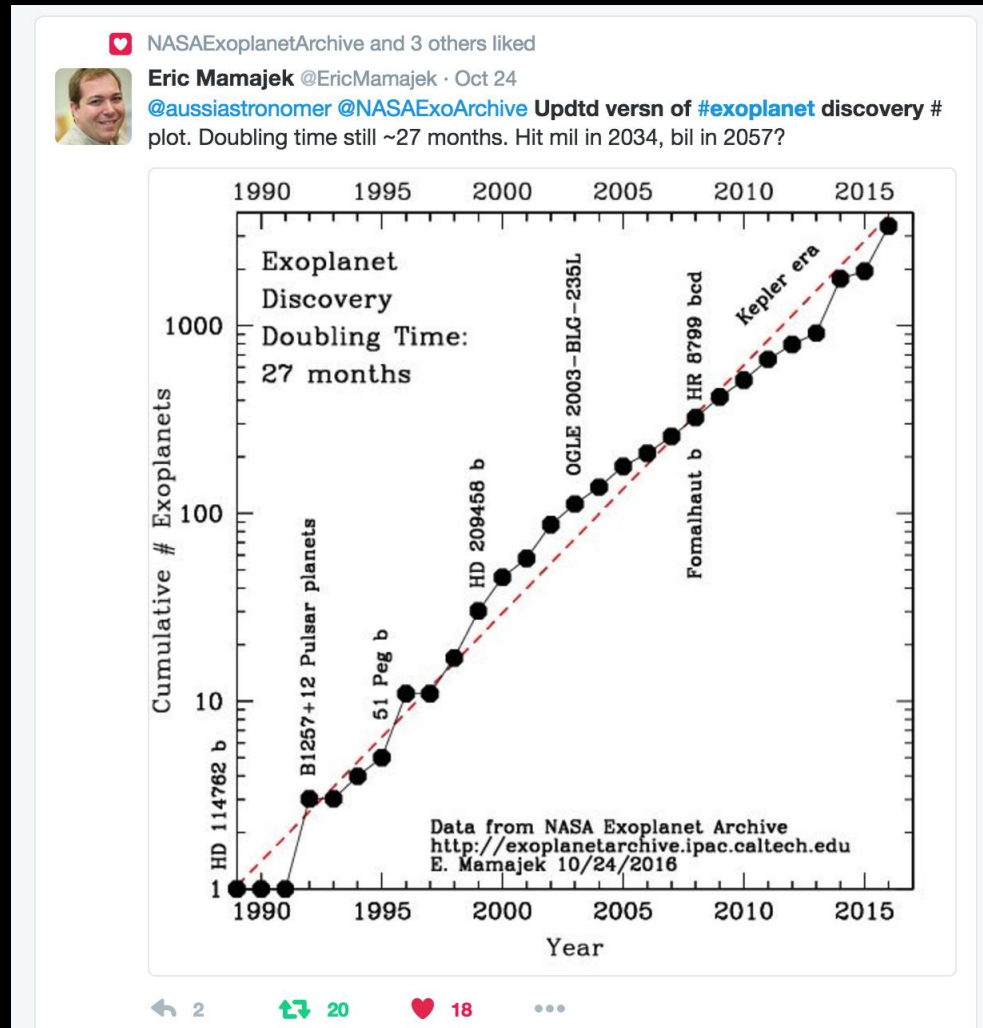
Credit: J. Christenson

Ground-Based Support for Space Missions
Partnering to Enable Key Projects for Strategic Reasons

Keck Observatory: (1/6 partner)
Key SMD Project and GO
Investigations

Large Binocular Telescope Interferometer:
Exozodiacal Dust Survey
University of Arizona

NN-EXPLORE using WIYN Telescope
NEID Precision Radial Velocity Instrument

Exoplanet Exploration Program

Serving the exoplanet science community by implementing NASA's space science vision for exoplanets

	Today	*Enabled Science*	Future	*Enabled Science*
Discover				
Characterize				
Identify Worlds that Could Harbor Life				
Community Support				

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You Had Me at Habitable

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Enabling Science in Future

	Future	Enabled Science
Discover	• WFIRST Microlensing Survey	• Census for long period planets
Characterize	• NEID GO	• Exoplanet Mass
	• WFIRST Coronagraph	• Reflected Light Spectroscopy
	• Original Probe Studies (Coronagraph, Starshade)	• Reflected Light Spectroscopy
	• OST	• Reflected Light Spectroscopy

WFIRST Microlensing Census for Exoplanets
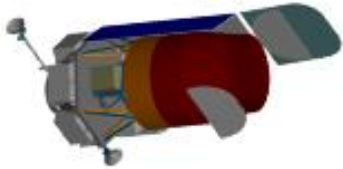
Together, Kepler and WFIRST-AFTA complete the statistical census of planetary systems in the Galaxy.
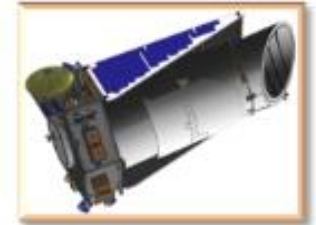
WFIRST-AFTA will:

- Detect 2800 planets, with orbits from the habitable zone outward, and masses down to a few times the mass of the Moon.

- Be sensitive to analogs of all the solar system's planets except Mercury.

- Measure the abundance of free-floating planets in the Galaxy with masses down to the mass of Mars
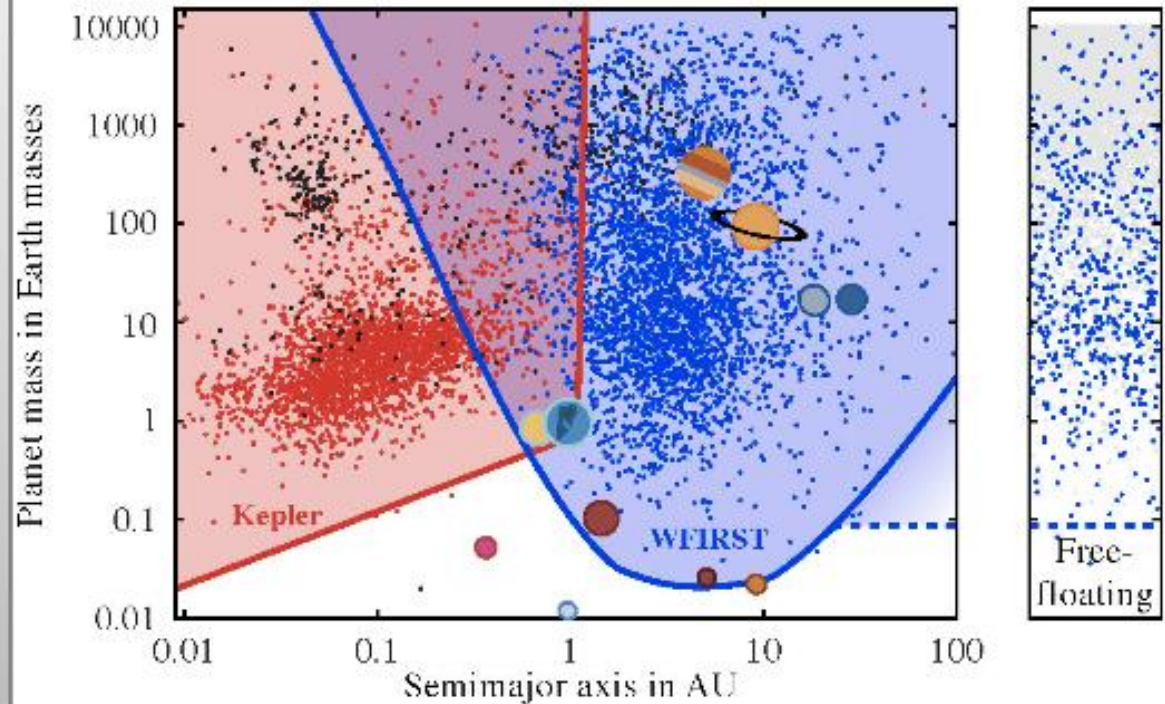
Credit: D. Bennett, M. Penny

Wide Field Infrared Survey Telescope (WFIRST)

Dark Energy, Infrared Survey… and Alien Worlds

- WFIRST in Phase A

- All technology milestones were met on time
  - Five for IR Detector, now at TRL 6
  - Nine for Coronagraph, now at TRL 5

- Actively studying making WFIRST starshade-ready.

- Reviews for SRR/MDR: delayed to allow independent external review

- https://www.nasa.gov/feature/nasa-taking-a-fresh-look-at-next-generation-space-telescope-plans

Credit: NASA/GSFC

NN·EXPLORE
Partnership for Exoplanet Discovery and Characterization
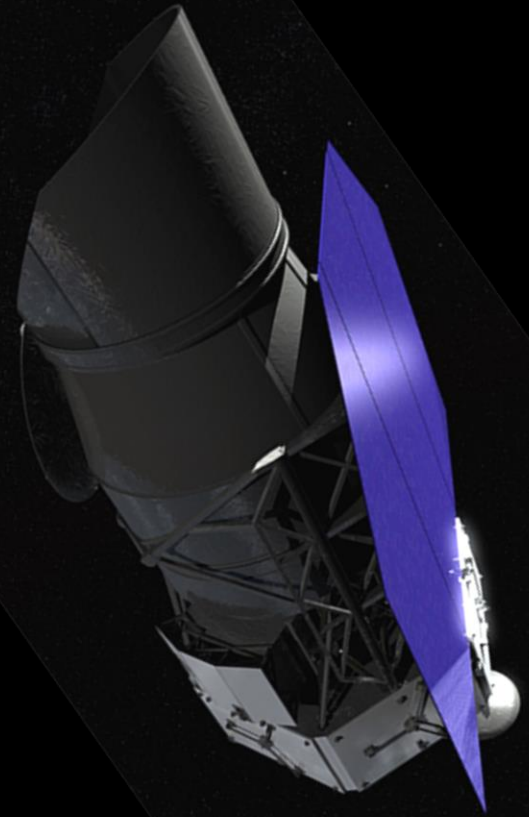
- Extreme precision radial velocity spectrometer (<0.5 m/s) for WIYN telescope

- Laser frequency comb reference

- Plan for instrument commissioning: August 2019

- Ongoing Guest Observer program using NOAO share of telescope time for exoplanet research.

- Please propose!

NN-Explore Exoplanet Investigations with Doppler Spectroscopy

PI: S. Mahadevan
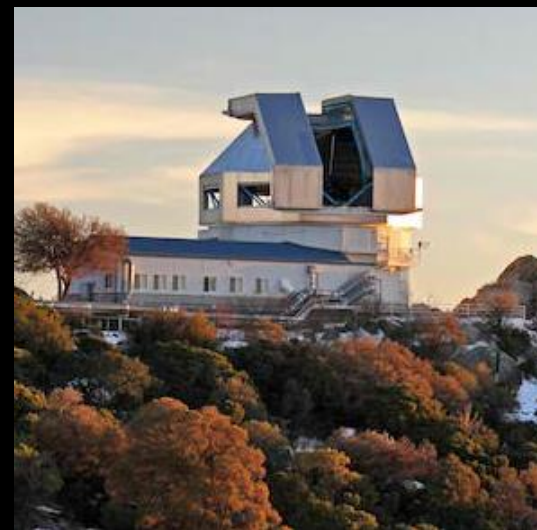
NOAO 3.5-m WIYN Telescope, Kitt Peak National Observatory, Arizona

NESSI on WIYN 3.5m Observatory, Kitt Peak
The NASA Exoplanet Star (and) Speckle Imager

- Speckle images in two simultaneous colors

- Resolution at or near diffraction limit

- Companion detection and characterization to delta magnitudes of ~5

- PI: Steve Howell, NASA ARC

http://www.wiyn.org/Instruments/
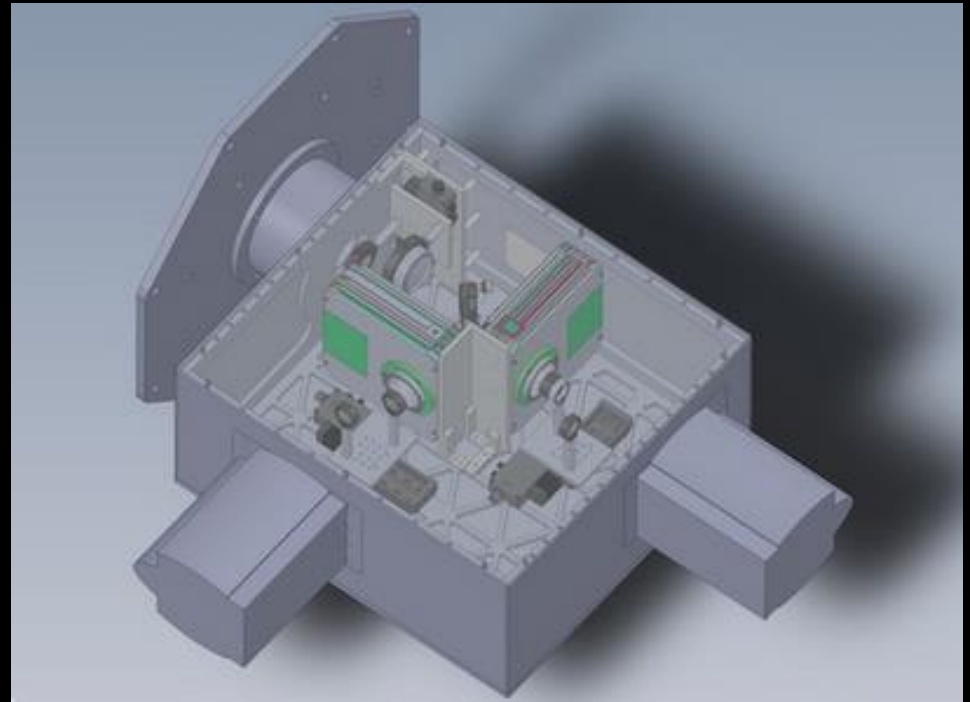
A Familiar Habitable Zone

Credit: Luc Forsyth

Exoplanet Exploration Program

Serving the exoplanet science community by implementing NASA's space science vision for exoplanets

	Today	*Enabled Science*	Future	*Enabled Science*
Discover				
Characterize				
Identify Worlds that Could Harbor Life				
Community Support				

Show Me the Planets!

You Had Me at Habitable

You Had Me at Habitable
Enabling Science Today

	Today	Enabled Science
Identify Worlds that Could Harbor Life	• Large Binocular Telescope Interferometer • Technology - Competed • Starshade Technology Development • Starshade Readiness Working Group • Segmented Coronagraph Design and Analysis • Telescope Stability Workshop	• Exozodiacal Dust survey • Increasing TRL feasibility • Decreasing inner working angle • Increasing outer working angle • Increasing starshade suppression • Minimizing segmented mirror edge diffraction • Increasing coronagraph contrast

Large Binocular Telescope Interferometer
Measuring HZ Exozodiacal Dust to Inform Designs of Future Missions

Credit: ESO/Y. Beletsky

- 35-star survey, September 2018

- Progress: 26 stars observed

- Measurement Precision: ~12 zodi, one star one sigma

Phil Hinz, PI

A THE UNIVERSITY OF ARIZONA

Dust rings
Star
Planet

Credit: NASA/GSFC

23
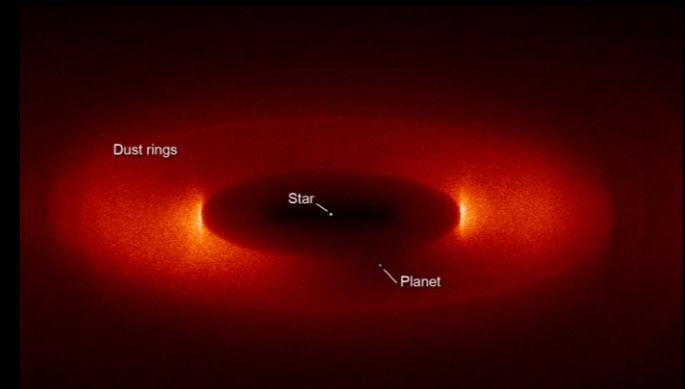
Strategic Astrophysics Technology – TDEM

Advancing Technology Readiness towards next Decadal Survey
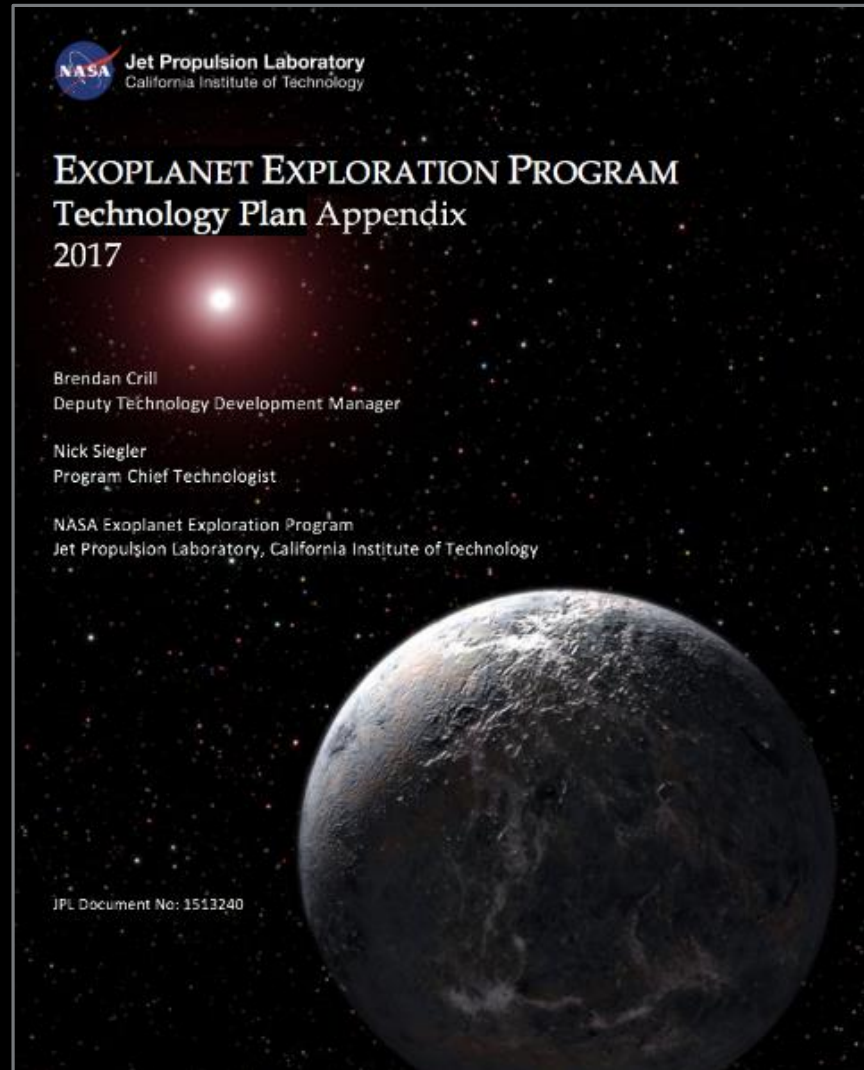
Appendix revision published January 2017

NASA Exoplanet Science Institute

- Sagan Summer School, July 2016
  "Is there a Planet in my Data?"

- Sagan Summer School, August 2017
  "Microlensing in the Era of WFIRST"

- NASA/Keck times (90 nights/yr) supports Exoplanets, Cosmic Origins, Physics of the Cosmos and Solar System Science

- Exoplanet Archive tracks exoplanet population and Kepler pipeline products

- ExoFOP supports Kepler & K2 sources follow-up
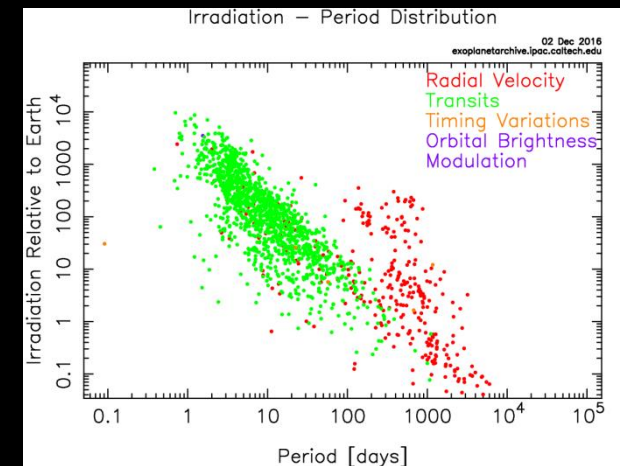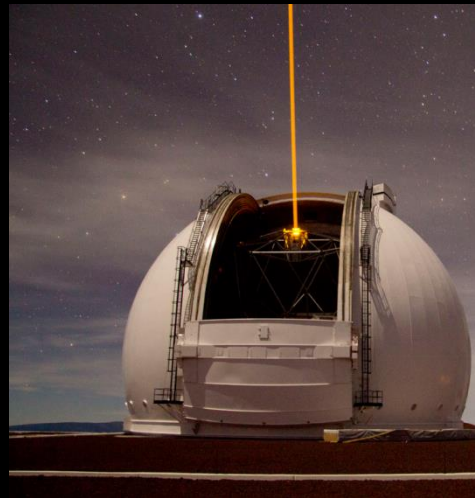
How Much Longer Can Mamajek's Law Last?

Credit: J. Christiansen

Exoplanet Exploration Program

Serving the exoplanet science community by implementing NASA's space science vision for exoplanets

	Today	*Enabled Science*	Future	*Enabled Science*
Discover				
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Show Me the Planets!

You Had Me at Habitable

You Had Me at Habitable

Enabling Science in Future

	Future	Enabled Science
Identify Worlds that Could Harbor Life	• Current Probe Starshade - WFIRST Rendezvous (Seager, Kasdin)	• Reflected Light Spectroscopy
	• LUVOIR	• Reflected Light Spectroscopy
	• HabEx	• Reflected Light Spectroscopy
	• OST	• Reflected Light, Transmission Spectroscopy
	• Current Probe Precision RV in Space (Plavchan)	• Mass Measurements
	• Standard Definitions and Evaluation Team	

Possible New Worlds Exoplanet Telescopes

(mid 2030s)
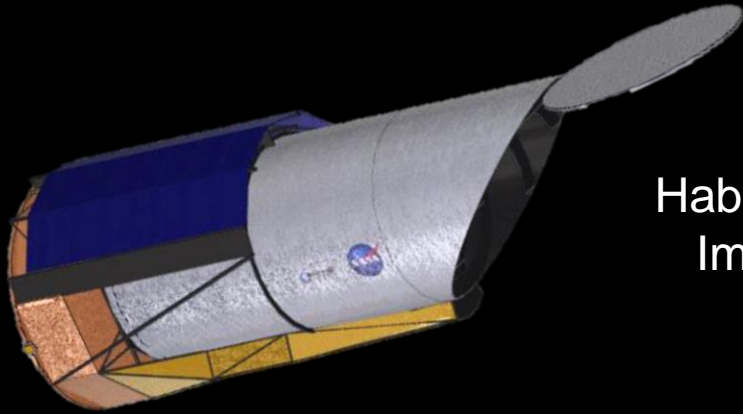
Habitable Exoplanet
Imaging Mission
(HabEx)

Large Ultra-Violet
Optical Infrared
Telescope (LUVOIR)

Origins Space
Telescope (OST)

Medium-Scale Space Mission Concepts

Announced by NASA March 20

PI	Affiliation	Title
Camp, J.	NASA's Goddard Space Flight Center	Transient Astrophysics Probe Concept Study
Cooray, A.	Univ. California, Irvine	Cosmic Dawn Intensity Mapper
Danchi, W.	NASA's Goddard Space Flight Center	Cosmic Evolution through UV spectroscopy (CETUS)
Glenn, J.	Univ. of Colorado	Galaxy Evolution Probe
Hanany, S.	Univ. of Minnesota	Inflation Probe Mission Concept Study
Mushotzky, R.	Univ. of Maryland	AXIS: A High Spatial Resolution X-ray Probe Satellite
Olinto, A.	Univ. of Chicago	Concept Study of the Probe Of Extreme Multi Messenger Astrophysics (POEMMA)
Plavchan, P.	Missouri State Univ.	EarthFinder: A Diffraction-Limited Precise Radial Velocity Observatory in Space (*Partial selection*)
Ray, P.	Naval Research Laboratory	STROBE-X: X-ray Timing and Spectroscopy on Dynamical Timescales from Microseconds to Years
Seager, S.	Massachusetts Institute of Technology	Starshade Rendezvous (*Partial selection*)

Coronagraph/Telescope Technology Needs

Contrast

Coronagraph architectures

Deformable mirrors
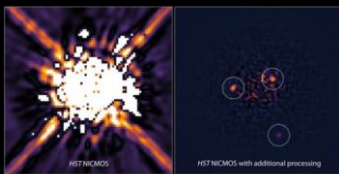
Image post-processing
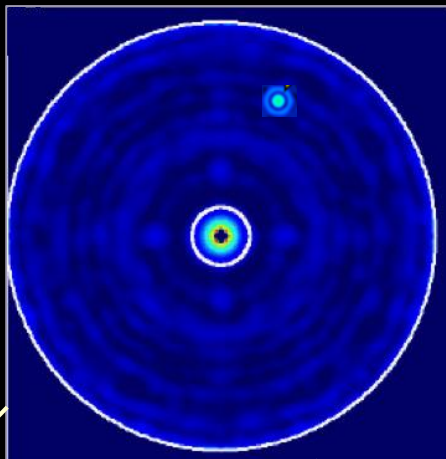
Angular Resolution

Large monolith
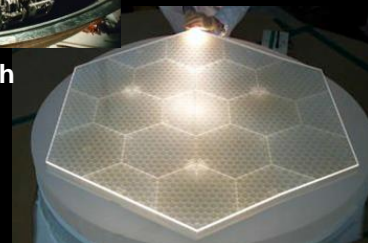
Segmented

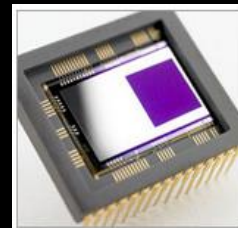**Contrast Stability**
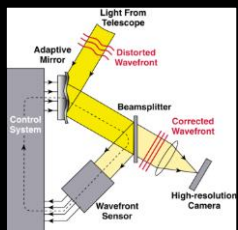
Wavefront sensing and control

Segment phasing and rigid body sensing and control

Telescope vibration sensing and control

Detection Sensitivity
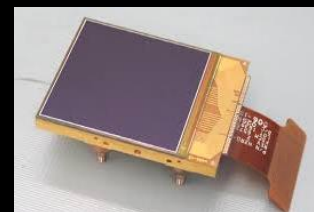
Ultra-low noise visible and infrared detectors

Starshade Technology Needs

1) Starlight Suppression

Suppressing scattered light off petal edges from off-axis Sunlight (S-2)

Suppressing diffracted light from on-axis starlight (S-1)

2) Formation Sensing and Control

Maintaining lateral offset requirement between the spacecrafts (S-3)

3) Deployment Accuracy and Shape Stability
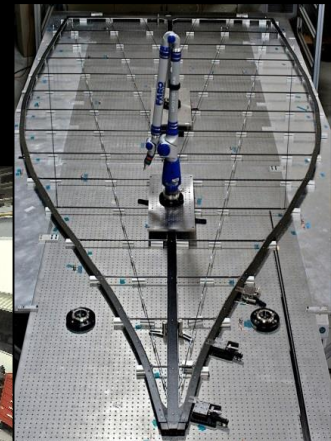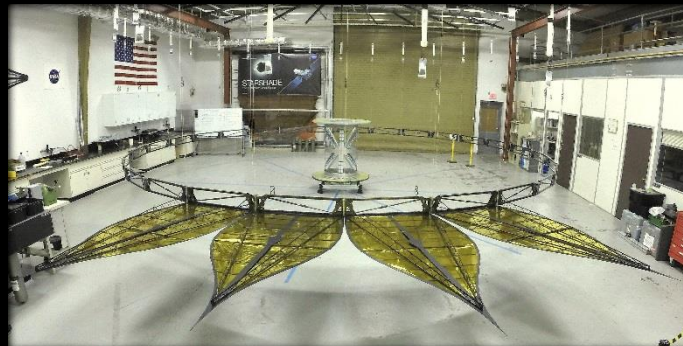
Fabricating the petals to high accuracy (S-4)

S-# corresponds to ExEP Starshade Technology Gap number
http://exoplanets.nasa.gov/exep/technology/gap-lists

Positioning the petals to high accuracy, blocking on-axis starlight, maintaining overall shape on a highly stable structure (S-5)
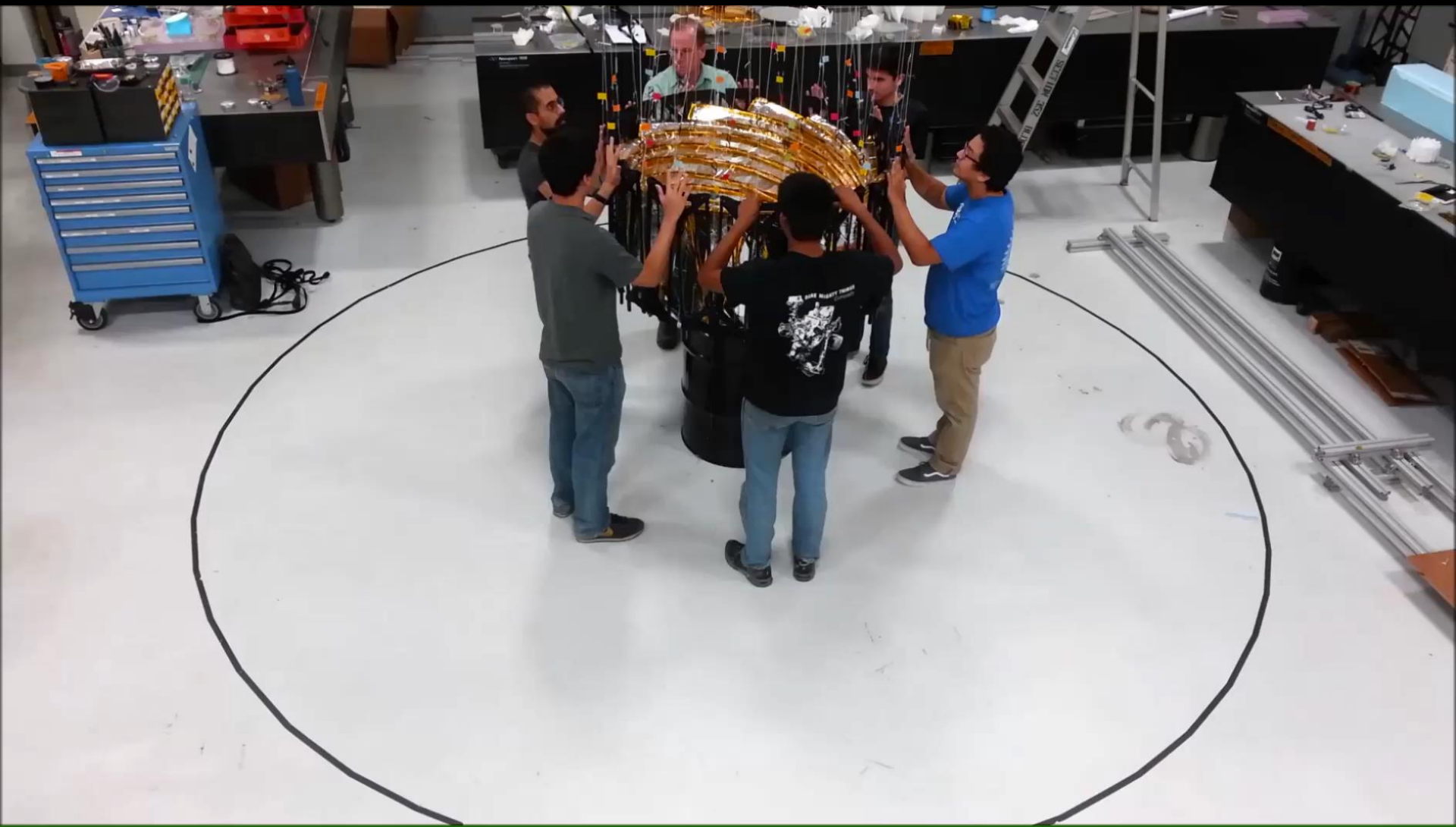
WFIRST Starshade-Ready
Accommodation Study to Enable a Rendezvous at L2

- WFIRST Starshade could directly image habitable-zone exo-earths in late 2020s
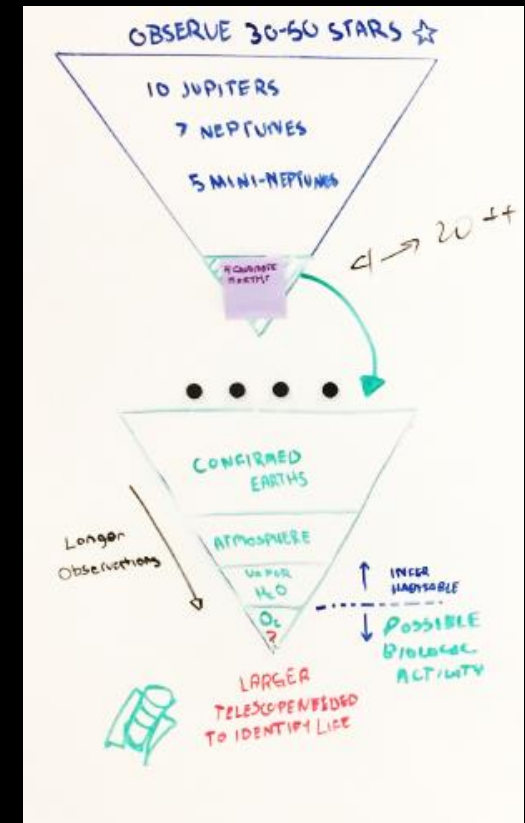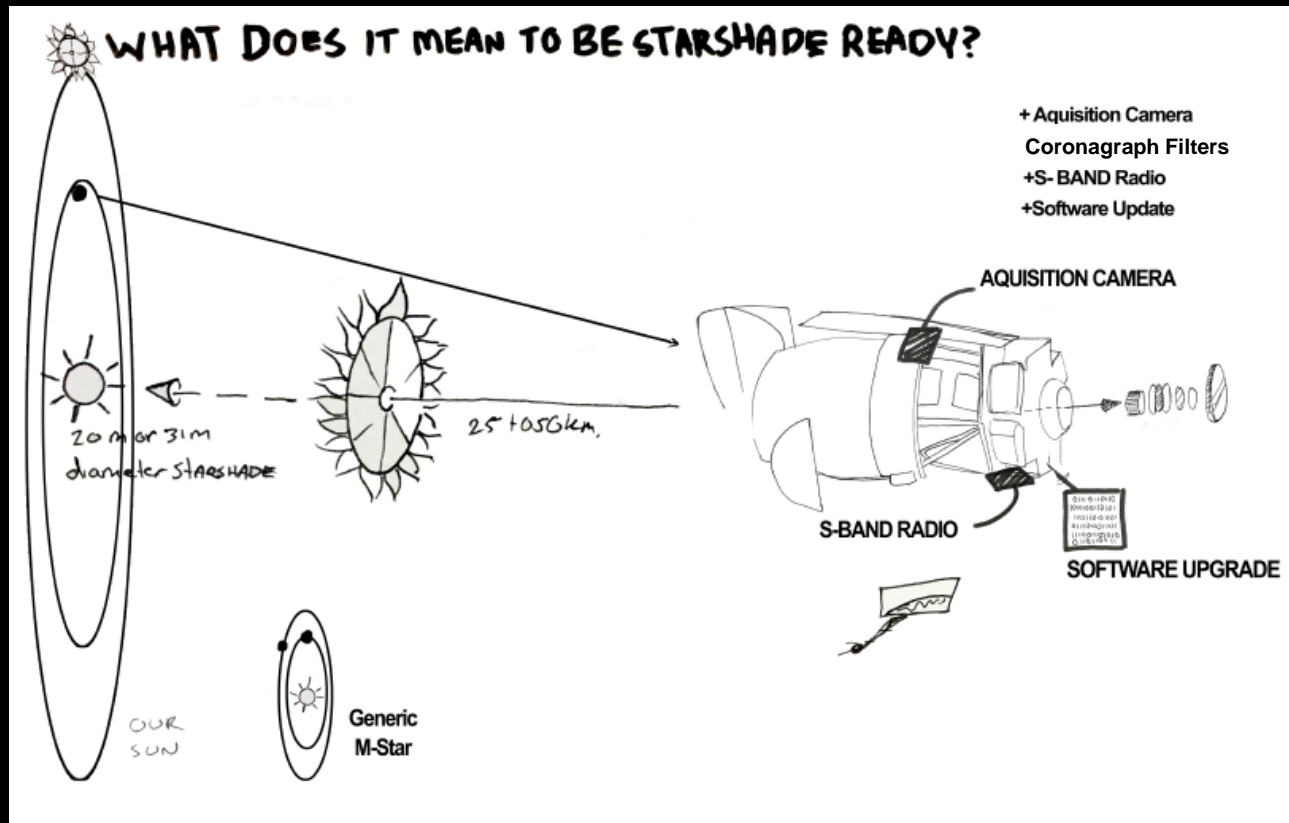
Early Inner Disk Deployment Trials at JPL

Exoplanet Exploration Program

Serving the exoplanet science community by implementing NASA's space science vision for exoplanets

	Today	*Enabled Science*	Future	*Enabled Science*
Discover				
Characterize				
Identify Worlds that Could Harbor Life				
Community Support				

Show Me the Planets!

You Had Me at Habitable

Serving the Community

| Community Support | NExScI:
• NASA Exoplanet Archive
• Exoplanet Follow-up Observing Program - Kepler/K2/TESS
• NASA Keck Time - GO
• NN-EXPLORE - GO
• Sagan Summer Workshop
• Sagan Fellowships
• Community support (workshops, conferences)

• Support to ExoPAG and SAGs
• Communication Products
• Education Products

• People Resources: Program Scientists, Technologists, Managers, Communications, Education | • Archive provides the ability to do orbit prediction and observability for space missions on all of the confirmed planets and candidates as well as the users own targets.
• ExoFOP supports Kepler, K2, TESS
• GO serves current observers
• Sagan trains next generation of scientists

• Scientific Community support

• SOC members, workshop members, review boards, technology strategy, engineering troubleshooters, Invited speakers, communication and education resources |

NASA Exoplanet Science Institute

- **Sagan Summer School**, August 2017 "Microlensing in the Era of WFIRST"

- **NASA/Keck time** (90 nights/yr) supports Exoplanets, Cosmic Origins, Physics of the Cosmos and Solar System Science

- **Exoplanet Archive** tracks exoplanet population and Kepler pipeline products

- **Exoplanet Follow-up Observing Program** supports Kepler & K2 sources follow-up

In the HZ

Confirmed

Candidates
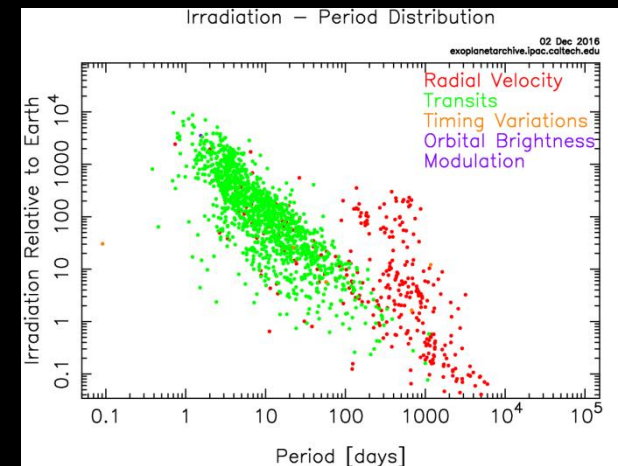
Exoplanet Communications

Data Visualization Tools and New Thematic Exoplanet Hub

exoplanets.nasa.gov
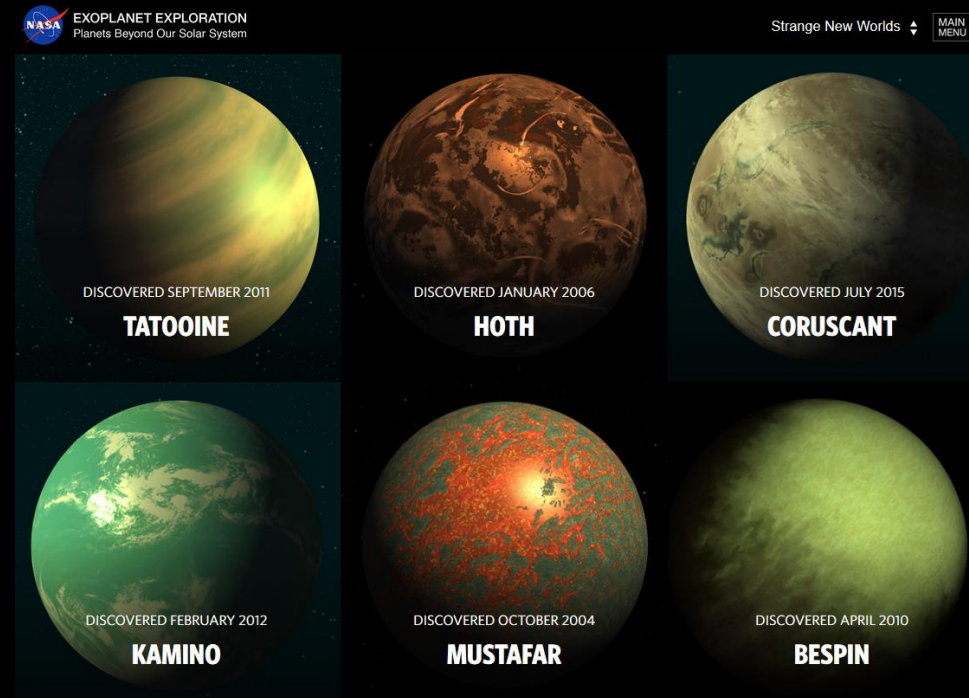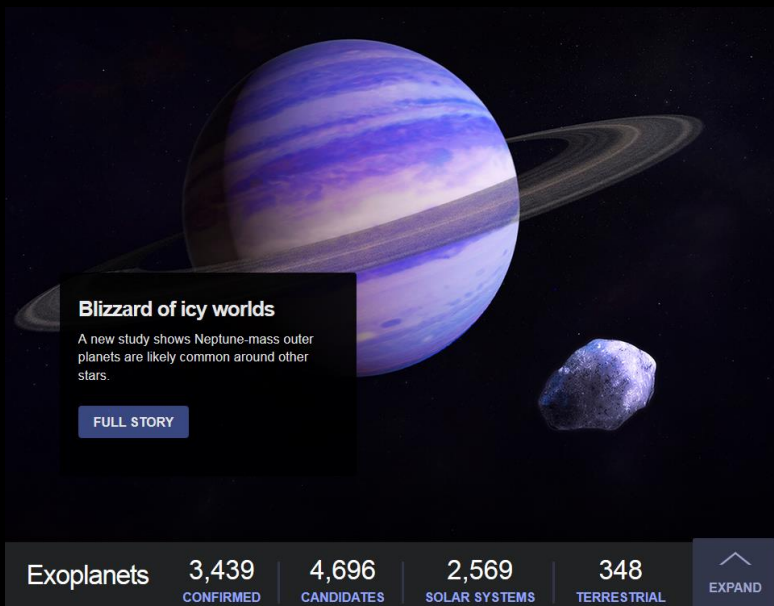
Replaced exoplanets.jpl.nasa.gov
Exoplanet-thematic content featuring
content across NASA.

3D, interactive planet renderings
Custom planet textures can be created
for press releases.
(contact the Comm team in advance)

Exoplanet Travel Bureau
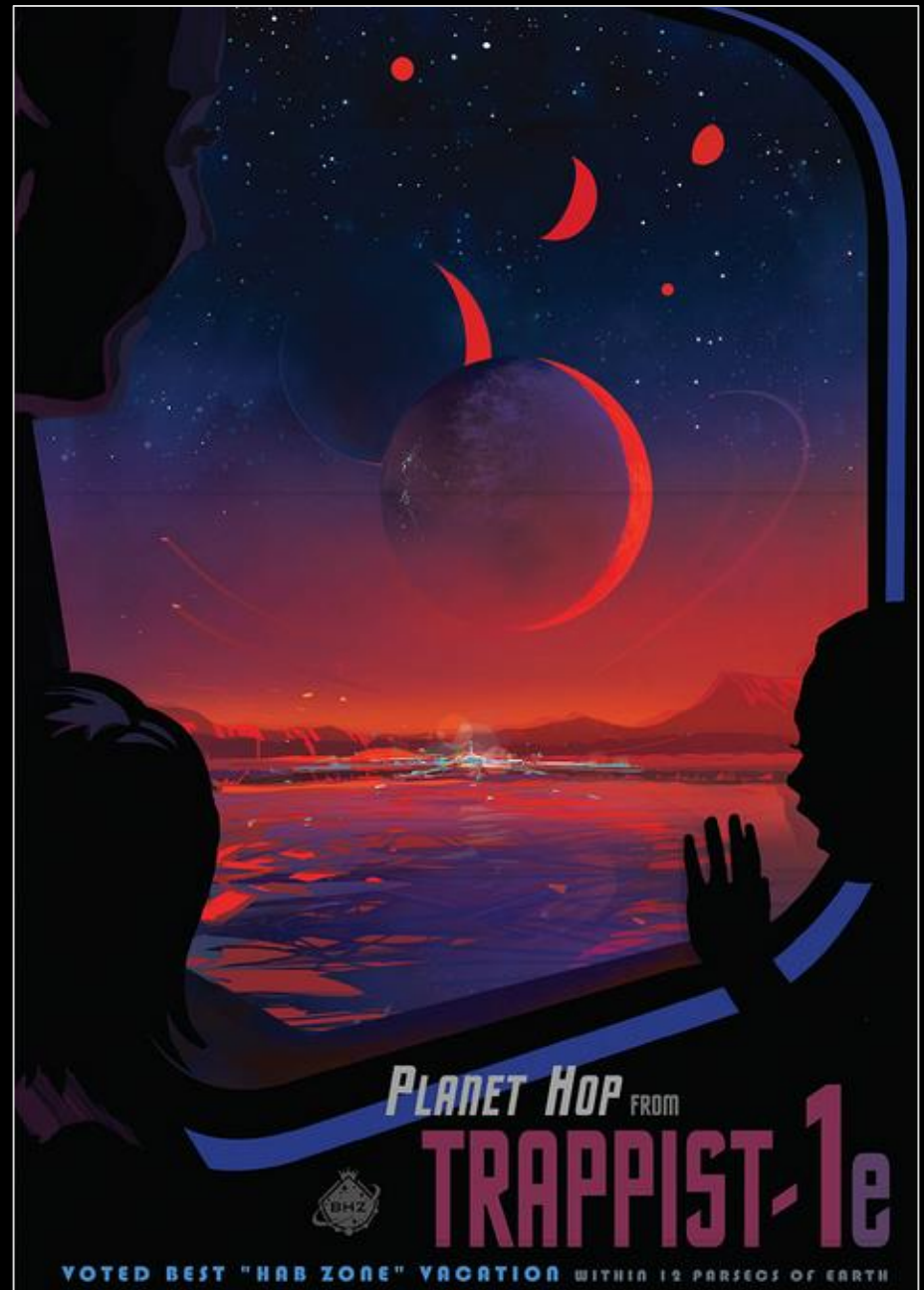
jpl.nasa.gov

Acknowledgements

National Aeronautics and
Space Administration

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